AD NO. 214007

WAL TR 401/250-1

AD A952360

WATERTOWN ARSENAL LABORATORIES

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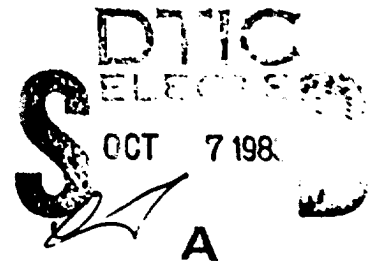
TECHNICAL REPORT NO. WAL TR 401/250-1

BY

DANIEL M. DALEY, JR.

CARL E. HARTBOWER

MAY 1959

O.O. PROJECT: TB4-003, MATERIALS FOR
LIGHTWEIGHT CONSTRUCTION
D/A PROJECT: 5B93-32-003

WATERTOWN ARSENAL
WATERTOWN 72, MASS.

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TITLE

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ABSTRACT

An investigation has been made of the weldability of three commercial heats of titanium, viz., two alpha-beta alloys containing 4% vanadium with 4% and 6% aluminum and one all-alpha alloy containing 2½% tin with 5% aluminum. Weldability was evaluated on the basis of tensile tests and notched-bar impact. Welding was accomplished by means of the inert-gas-shielded consumable-electrode process using both matching and unalloyed wire as filler material.

The tensile strength of the Ti-6Al-4V welded with matching filler was highest (152,000 psi); all of the materials gave 100% joint efficiency when welded with matching filler (attended by 7 - 13% elongation). With unalloyed filler the tensile strength of the weld deposit was somewhat lower and the weld metal ductility higher than with matching filler. Consequently, with unalloyed filler, tensile fractures occurred in the weld deposits at joint efficiencies of 90 - 96%. The improved ductility and loss of strength in the case of the welds made with unalloyed filler was attributed to the lower alloy content of the weld deposits.

With regard to notch toughness, the Ti-4Al-4V heat had an advantage over either of the other heats investigated. Moreover, the low-alloy alpha-beta welds obtained with unalloyed filler wire were markedly superior to both the alpha-beta welds obtained with matching filler wire and the all-alpha Al-Sn welds obtained with either unalloyed or matching filler wire. The detrimental effect obtained from the use of unalloyed wire in welding Ti-5Al-2½Sn was unexpected.

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REPORT APPROVED
Date- 26 may 59
WAL Board of Review
Chairman- WSW

INTRODUCTION

Background

In an earlier investigation at Watertown Arsenal Laboratories[1] the tensile properties and notch toughness of an inert-gas-shielded tungsten-arc weld in a single heat of the Ti-6Al-4V alloy were evaluated. As a basis of comparison a limited number of tests were also run on a single heat of Ti-5Al-2½Sn alloy. In each case the filler consisted of strip sheared from the plate being welded. The results are summarized in Table I.

TABLE I

Material		Weld Chemistry				Transverse Tensile			Tough-ness***
Type	Heat	COHN*	Al	V	Sn	Yield (.2%)	Ult. (psi)	R.A. (%)	ft-lb (-40°)
6Al-4V	M1801D	.25	5.69	3.34	--	132,000	152,000	32**	9
5Al-2½Sn	D30540B	.23	4.89	--	2.38	118,000	130,000	25**	10

*COHN is the sum of the carbon, oxygen, hydrogen, and nitrogen contents in weight-percent.
**Fracture occurred in the weld deposit.
***Modified (.197 x .788 x 2.12 inch) V notch Charpy impact notched in the weld deposit.

Because the above data obtained in the earlier investigation were limited (single heats), additional materials were procured for test.

Objective and Scope

It was the object of this investigation to compare the tensile and notched-bar-impact properties of three compositions in both the as-received and as-welded conditions. The materials were ¼-inch Ti-6Al-4V, Ti-4Al-4V, and Ti-5Al-2½Sn plate in the mill-annealed condition. Evaluation of the base metals and weld deposits was based on the mechanical properties as determined with a subsize tensile and the modified (.197 x .788 x 2.12 inch) V notch Charpy impact specimen.

MATERIALS

The materials used during this investigation together with their chemical analyses* are listed in Table II. This includes single heats of Ti-6Al-4V, Ti-4Al-4V, and Ti-5Al-2½Sn as ¼-inch plate together with alloy wire of matching composition and a single heat of unalloyed titanium wire. These materials were obtained from commercial suppliers in the annealed condition. The analyses are typical of commercially available materials.

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[1] DALEY, D. M., Jr., and HARTBOWER, C. E., "An Investigation of the Mechanical Properties of Metal-Arc Welded Ti-6Al-4V," WAL Report No. 401/250, The Welding Journal, vol. 36(4), (April 1957).

TABLE II

MATERIALS INVESTIGATED AND THEIR CHEMICAL ANALYSES

Material	Heat	Shape	C	O	H	N	Fe	Al	V	Sn
Ti-6Al-4V	M2443	1/4-in. plate	.022	.097	.0041	.013	.24	6.19	4.11	
Ti-4Al-4V	2G52235	1/4-in. plate	.021	.110*	.011*	.013	.06	4.34	3.71	
Ti-5Al-2½Sn	D1-220530	1/4-in. plate	.019	.195	.0088	.045	.33	5.08		2.43
Ti-6Al-4V	G52062	1/16-in. wire	.027	.119	.012	.026	.21	6.15	3.66	
Ti-4Al-4V	2G52235	1/16-in. wire	.038	.089	.014	.010	.11	4.38	3.81	
Ti-4Al-4V	M1802D	1/16-in. wire	.052	.091	.0062	.020	.12	4.18	3.90	
Ti-5Al-2½Sn	M270	1/16-in. wire	.052	.166	.0018	.025	.13	4.90		2.40
Ti-75A	M270	1/16-in. wire	.08	.106	.019	.060	.12			

Average of two analyses.

PROCEDURES

Welding Procedure

All weldments prepared during this investigation were made using the automatic inert-gas-shielded consumable-electrode process (Figure 1). Welding was accomplished in a single pass with both matching and unalloyed filler wire. Welding amperages and voltages were automatically recorded and the arc-travel speed held constant for all weldments. Besides inert-gas issuing from the welding head (primary shield), auxiliary shielding was provided by a trailing shield (Figure 2), which protected the top surface of the weld, and a grooved copper backup bar containing inert gas, which protected the underside of the weldment.
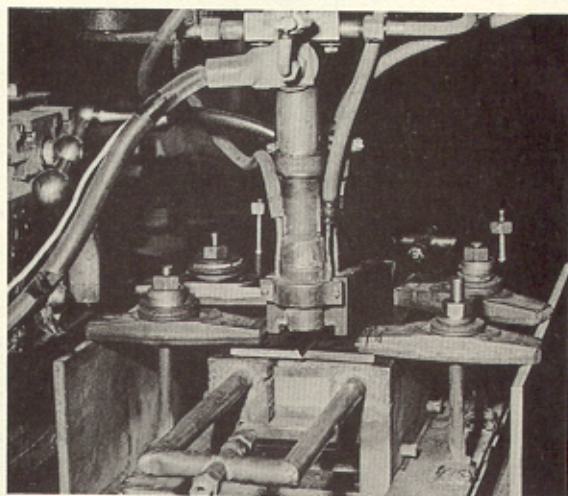

FIGURE I: AUTOMATIC INERT-GAS-SHIELDED CON-SUMABLE-ELECTRODE WELDING EQUIPMENT used for preparing weldments in 1/4-inch plate.
Wtn. 121-967

The details of the welding procedures used during this investigation follow:

a. Joint Design: 60° single V butt with a 1/8-inch land and a zero root opening using one weld pass in 1/4-inch plate.

b. Meter Reading: 385 - 395 amperes; 70 volts open and 36 - 38 volts closed circuit voltage; direct current, reverse polarity.

c. Arc-Travel Speed: 27 inches per minute.

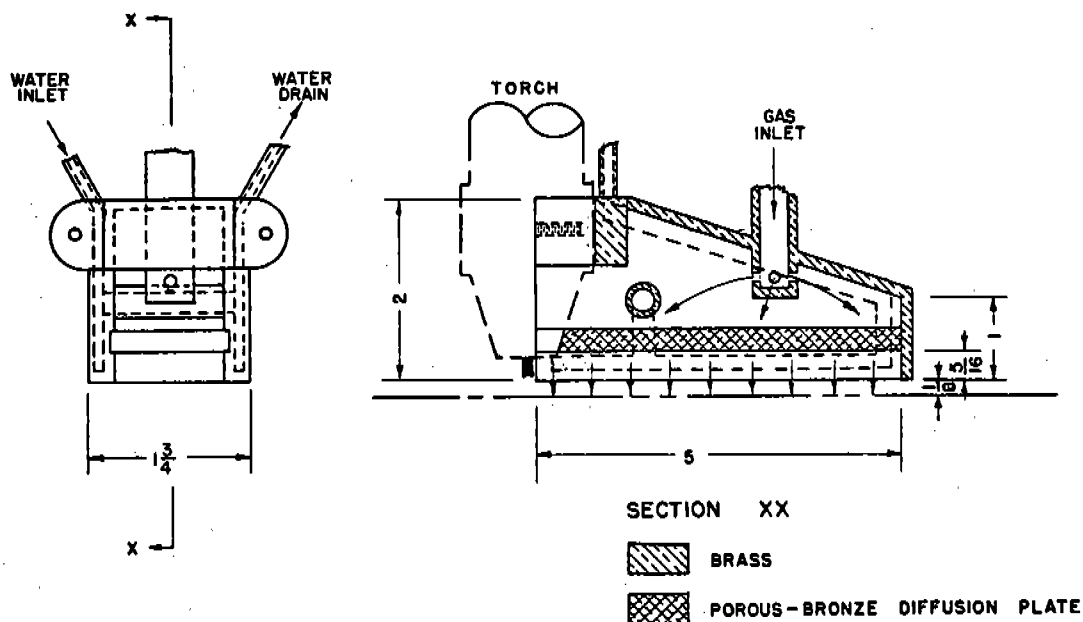SECTION XX

☒ BRASS

☒ POROUS-BRONZE DIFFUSION PLATE

FIGURE 2: TRAILING SHIELD for protecting the hot weld metal while solidifying and cooling.

    d.   Wire Feed Speed: 1/16-inch diameter bare-wire electrode at approximately 400 inches per minute.

    e.   Shielding: Primary - 100 cfh helium plus 10 cfh argon.
                                 Trail   - 100 cfh argon.
                                   Backup - Water-cooled copper.

The inert-gas used was a commercial welding grade of the highest purity commercially available for welding (99.92% argon and 99.95% helium).

Testing Procedure

Tensile properties were determined using a subsize specimen (Figure 3). The testing was conducted at a head speed of 0.020 inch per minute, and the tensile elongation was measured over a gage length of 0.75 inch.

The V notch impact transition curves were obtained using a modified V notch Charpy impact specimen in a standard impact machine with anvils modified so that the center of percussion of the pendulum coincided with the center of the impact specimen. This
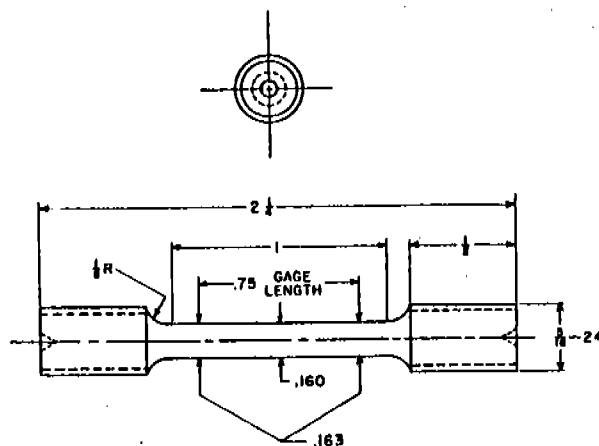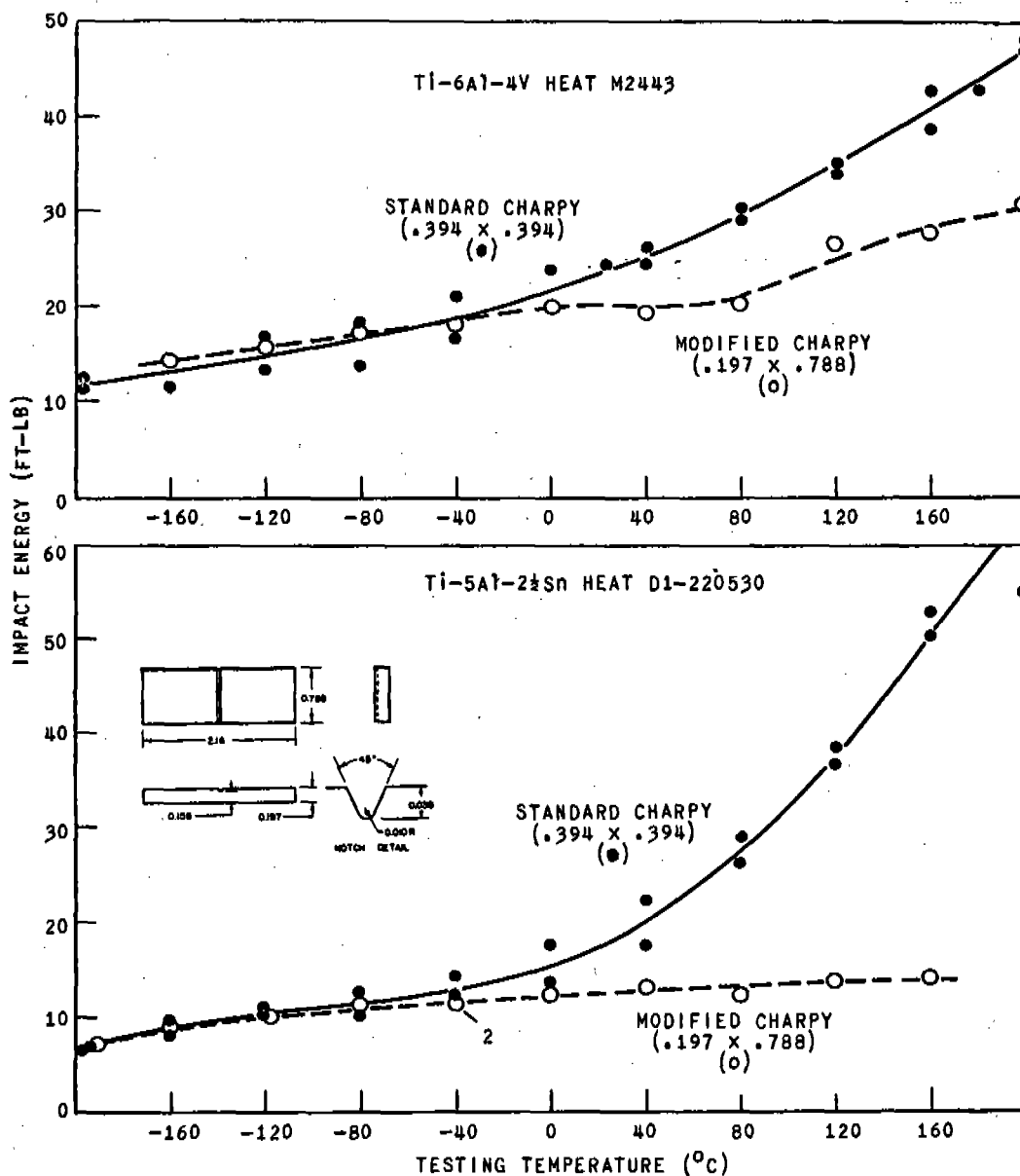

FIGURE 3: SUBSIZE TENSILE SPECIMEN

FIGURE 4: CORRELATION OF MODIFIED CHARPY WITH STANDARD CHARPY (UNWELDED PLATE)

specimen in unwelded plate has been found to provide a good correlation with the standard V notch Charpy impact specimen in the low-energy range (Figure 4).

A hardness survey was made for each of the weldments investigated. Vickers hardness impressions were placed at 0.02-inch intervals using a 10 Kg load, starting in the unaffected base metal and traversing through the heat-affected zone and deposited weld metal. The microstructures of the various base metals, their heat-affected zones and weld deposits were examined also, and typical structures recorded at X500. Specimens were etched using a solution of one part HF, one part HNO_3, and three parts glycerine.

Chemical Analysis

Chemical analyses for the deposited weld metals are shown in Table III. Note that in the case of weldments prepared with unalloyed filler material, the weld deposits contained appreciable amounts of the principal alloying elements (Al, V, and Sn) as the result of base-metal melting.

TABLE III

CHEMICAL ANALYSIS OF WELD DEPOSITS

Weld Code	Base Metal		Filler Metal		Chemical Analysis (Wgt %)							
	Type	Heat	Type	Heat	C	O	H	N	Fe	Al	V	Sn
A	6Al-4V	M2443	6Al-4V	G52062	.026	.122	.007	.020	.34	6.09	3.84	
B	4Al-4V	2G52235	4Al-4V	2G52235	.031	.116	.012	.018	.23	4.22	3.62	
C	4Al-4V	2G52235	4Al-4V	M1602D	.034	.123	.008	.015	.23	4.19	3.75	
D	5Al-2½Sn	D1-220530	5Al-2½Sn	(Unknown)	.043	.155	.006	.033	.17	4.78		2.23
E	6Al-4V	M2443	Ti-75A	M270	.053	.141	.009	.024	.14	3.15	2.14	
F	4Al-4V	2G52235	Ti-75A	M270	.053	.133	.012	.024	.11	2.31	2.09	
G	5Al-2½Sn	D1-220530	Ti-75A	M270	.059	.171	.008	.048	.24	3.01		1.43

In evaluating the effectiveness of the gas shielding during welding, a comparison was made between the estimated and the actual amounts of gaseous interstitial elements contained in the deposited weld metal. This estimate was based upon the assumption that the weld deposits were formed by combining approximately equal volumes of base metal and filler,* and that near-perfect shielding should prevent an appreciable pickup of interstitials from the air surrounding the inert-gas shield. Referring to Table IV it

TABLE IV

COMPARISON BETWEEN THE ESTIMATED AND
ACTUAL GAS CONTENTS OF WELD DEPOSITS

Weld Code	Oxygen				Hydrogen				Nitrogen			
	Est.	Actual	GAIN	%	Est.	Actual	LOSS	%	Est.	Actual	LOSS	%
A	.108	.122	.014	13	.008	.007	.001	8	.020	.020	0	0
B	.100	.116	.016	16	.012	.011	.001	12	.012	.018	-.006	-
C	.101	.123	.022	22	.009	.008	.001	9	.017	.015	.002	12
D	.180	.155	-.025		.008	.006	.002	25	.035	.033	.002	3
E	.102	.141	.039	38	.012	.009	.003	25	.037	.024	.013	35
F	.108	.133	.025	23	.015	.012	.003	20	.037	.024	.013	35
G	.150	.171	.021	13	.014	.008	.006	43	.052	.048	.004	8

*Examination of the cross section of several of the weldments indicated that the percentage of base metal melted was between 45 and 50%.

can be seen that in all but one of the weldments, the actual amount of oxygen was greater than the estimated value. This indicates a pickup of oxygen during welding. In the case of hydrogen the content was in all cases less than the estimated value, indicating that hydrogen evolved during welding. In the case of nitrogen five of the seven welds indicated the actual nitrogen to be less than the estimate. This also indicates that nitrogen evolved during welding. The literature is consistent in showing that hydrogen evolves during welding and that oxygen is picked up. The data on nitrogen, however, are conflicting. The findings of this report confirm data reported by Battelle Memorial Institute,[2] where for 63 weldments tested (using a matching filler) more than 50% showed the nitrogen content of the weld deposit to be less than that of the base metal. Earlier work at Watertown Arsenal Laboratories,[3] however, indicated that the nitrogen content of weld deposits was less than that estimated in only two of six welds investigated. From theoretical considerations evolution of nitrogen would not seem likely.

Figure 5 is a plot of the alloy content of the base metal versus the alloy content of the weld deposit using unalloyed filler. For the particular welding conditions used in this investigation it is possible by means of this curve to estimate the amount of alloying element that will be tranferred from the alloy base metal to the weld deposit when welding with unalloyed titanium filler material. Thus, for the welding conditions used during this investigation, a base containing 3% of a given alloying element would provide slightly more than 1½% of that element to the weld deposit.
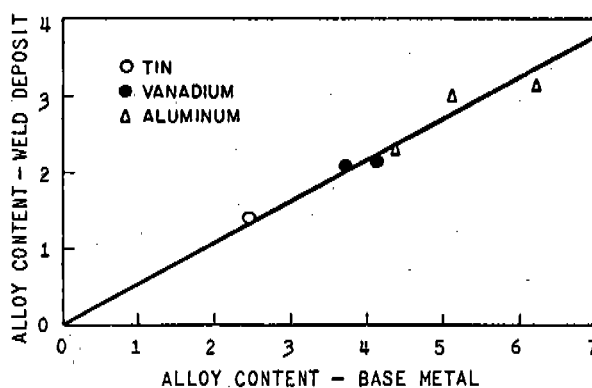

FIGURE 5: RELATIONSHIP BETWEEN WELD AND BASE METAL ALLOY CONTENT

Tensile Tests

The tensile properties, as determined with a subsize tensile specimen (see Figure 3), for the as-received annealed plate material are shown in Table V. Note that the tensile properties are approximately the same for specimens taken both longitudinal and transverse to the direction of rolling. The heat of Ti-6Al-4V investigated had the greatest ultimate tensile strength (148,000 psi), with the Ti-5Al-2½Sn next (138,000 psi), and the Ti-4Al-4V lowest (127,000 psi).

[2] LEWIS, E. J., KOHN, M. L., and FAULKNER, G. E., "The Effects of Interstitial Elements on Welds in Alpha-Beta Titanium Alloys," WAL Report No. 401/97-35.

[3] HARTBOWER, C. E. and DALEY, D. M., Jr., "Alloy Weld Deposits in Unalloyed Titanium Base Metal," WAL Report No. 401/216, The Welding Journal, vol. 33(7&8), (July-August 1954).

TABLE V

TENSILE PROPERTIES OF BASE MATERIALS*

Material	Heat	Direction	Yield Strength (psi)			Ultimate (psi)	Elon. (%)	R.A. (%)
			.01% Offset	.1% Offset	.2% Offset			
Ti-6%Al-4%V	M2443	Transverse	126,000	134,000	-135,000	148,000	16	42
		Longitudinal	128,000	144,000	·144,000	147,000	15	49
Ti-4%Al-4%V	2G52235	Transverse	105,000	116,000	118,000	127,000	14	44
		Longitudinal	101,000	113,000	116,000	126,000	15	43
Ti-5%Al-2½%Sn	D1-220530	Transverse	132,000	133,000	133,000	138,000	20	43
		Longitudinal	132,000	133,000	133,000	138,000	19	42

*Average of two tests.

The as-welded tensile properties of the weldments were also determined using the subsize tensile specimen. Specimens were taken both transverse and longitudinal to the direction of the weld deposit. The transverse specimens included both deposited weld metal and heat-affected base metal, while the longitudinal specimens were made up entirely of deposited weld metal. The data obtained are shown in Table VI. The tensile joint efficiency was determined by dividing the ultimate tensile strength of the weld joint (as measured by a transverse specimen) by the ultimate tensile strength of the as-received base metal.

TABLE VI

TENSILE PROPERTIES OF WELDMENTS*

Base Metal		Filler Metal		Weld Direc.	Yield Strength			Ultimate (psi)	Elon (%)	RA (%)	Frac. Loc.	Joint Effic. (%)
Type	Heat	Type	Heat		.01%	.1%	.2%					
6Al-4V	M2443	6Al-4V	G52062	Trans.	100,000	131,000	138,000	152,000	**	44	HAZ	102
6Al-4V	M2443	6Al-4V	G52062	Long.	97,000	127,000	134,000	154,000	7	14	***	
4Al-4V	2G52235	4Al-4V	2G52235	Trans.	78,000	107,000	115,000	128,000	--	42	HAZ	101
4Al-4V	2G52235	4Al-4V	2G52235	Long.	79,000	109,000	116,000	132,000	10	22	Weld	
4Al-4V	2G52235	4Al-4V	M1802D	Trans.	86,000	110,000	116,000	128,000	--	44	HAZ	101
4Al-4V	2G52235	4Al-4V	M1802D	Long.	89,000	112,000	120,000	134,000	10	20	Weld	
5Al-2½Sn	D1-220530	5Al-2½Sn	unknown	Trans.	111,000	128,000	132,000	142,000	--	38	HAZ	102
5Al-2½Sn	D1-220530	5Al-2½Sn	unknown	Long.	116,000	132,000	135,000	144,000	13	28	Weld	
6Al-4V	M2443	Ti-75A	M270	Trans.	102,000	120,000	126,000	134,000	--	30	Weld	90
6Al-4V	M2443	Ti-75A	M270	Long.	94,000	108,000	114,000	122,000	16	42	Weld	
4Al-4V	2G52235	Ti-75A	M270	Trans.	88,000	108,000	114,000	122,000	--	25	Weld	96
4Al-4V	2G52235	Ti-75A	M270	Long.	86,000	106,000	107,000	116,000	14	33	Weld	
5Al-2½Sn	D1-220530	Ti-75A	M270	Trans.	108,000	122,000	124,000	130,000	--	34	Weld	94
5Al-2½Sn	D1-220530	Ti-75A	M270	Long.	100,000	116,000	119,000	127,000	17	33	Weld	

*Data are an average of two tests.

**Data on elongation for transverse welded specimens have been omitted because there is both weld deposit and heat-affected zone included within the gage length, and such data could lead to erroneous conclusions.

***Longitudinal specimens consisted entirely of weld metal.

Based on a comparison of data in Tables V and VI the following observations were made:

a. In the case of weldments prepared with matching filler metal

(1) The ultimate tensile strength as indicated by transversely welded specimens was greater than that of the as-received base metal, resulting in a tensile-joint efficiency somewhat greater than 100%. The transverse specimens welded with matching filler all failed in the heat-affected zone of the weld joint, and the ultimate tensile strength as indicated by longitudinally welded specimens (all-weld-metal) was consistently greater than that indicated by transversely welded specimens.

(2) The low yield strengths in the Al-V alloys welded with matching filler material indicate that the cooling rates were sufficiently rapid to produce an effect similar to that achieved by *solution treatment*. This suggests that the alpha-beta welds might have been strengthened if an aging treatment had been employed after welding.

(3) Ductility of the weld metal as measured by reduction of area in the longitudinally welded specimens was considerably less than that of the base metal. In the case of the transversely welded specimens all of which fractured in the heat-affected base metal, the reduction of area was approximately the same as that of the base metal.

b. In the case of weldments prepared with unalloyed filler metal

(1) The ultimate tensile strength as indicated by transversely welded specimens was less than that of the base metal, resulting in a lower tensile-joint efficiency than that obtained when welding with matching filler metal. All specimens failed in the weld metal.

(2) Although the yield strengths were low as compared with those of the unwelded base metals, they were not greatly lower than those obtained using matching filler wire.

(3) Ductility of the weld metal as measured by reduction of area in the longitudinally welded specimens was appreciably greater than that obtained with matching filler.

Notch-Bar Impact Tests

The V notch Charpy impact transition curves for the as-received plate are presented in Figure 6. These curves show that there is little or no difference between the longitudinal and transverse impact properties for the Ti-4Al-4V and Ti-5Al-2½Sn heats investigated. However, in the case of the Ti-6Al-4V heat, the impact specimens taken transverse to the direction of rolling absorbed 5 to 7 ft-lb more energy than the specimens taken in the longitudinal direction. The impact energy absorbed by the three
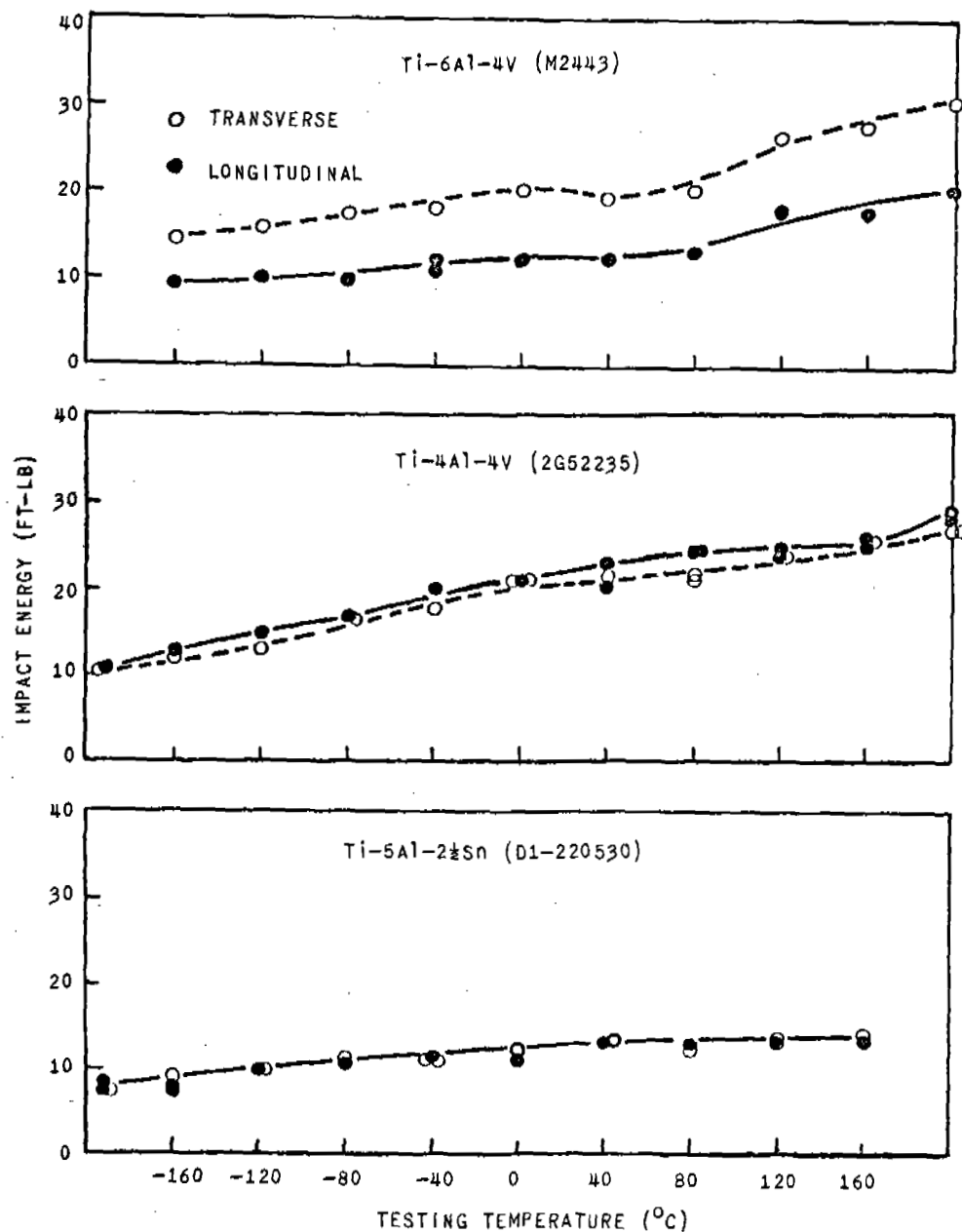
FIGURE 6: NOTCH TOUGHNESS OF ALLOYED TITANIUM BASE METALS –
Transition curves were obtained in two orientations by means
of the modified Charpy impact specimen.

titanium plate materials at room temperature and at -40°C is listed in Table VII. Note that Ti-4Al-4V heat had a slight advantage over the other two composition types investigated.

TABLE VII

NOTCH TOUGHNESS OF BASE MATERIALS

Base Material			Impact Energy (ft-lb)			
			Transverse		Longitudinal	
Type	Heat	COHN*	Room Temp.	-40°C	Room Temp.	-40°C
Ti-6Al-4V	M2443	.136	20	18	13	12
Ti-4Al-4V	2G52235	.155	21	18	22	19
Ti-5Al-2½Sn	D1-220530	.268	13	11	13	11

*COHN is the sum of the carbon, oxygen, hydrogen, and nitrogen contents in weight-percent.

The impact transition curves for the various weld deposits are plotted in Figure 7. It can readily be seen that depositing unalloyed titanium filler in Al-V-alloy base material produced weld deposits of appreciably greater toughness than matching filler material. In the case of the Ti-5Al-2½Sn weldments, matching filler produced weld deposits having somewhat greater toughness than those prepared with unalloyed titanium filler.

Table VIII has been included to facilitate comparisons between the different weld-metal base-metal combinations. The superior toughness of low-alloy alpha-beta titanium[4] and the advantage in welding alpha-beta alloys with unalloyed titanium filler[5] has been reported earlier. It was to be expected, therefore, that the weld deposits containing approximately 2% of beta-stabilizing element would have better toughness than those containing over 3-1/2%.

TABLE VIII

NOTCH TOUGHNESS OF WELD DEPOSITS

Base Metal		Filler Metal		Chemistry of Weld Deposits				Impact Energy (ft-lb)	
Type	Heat	Type	Heat	COHN	Al	V	Sn	RT	-40°C
6Al-4V	M2443	6Al-4V	G52067	.175	6.09	3.84		11	9
4Al-4V	2G52235	4Al-4V	2G52235	.177	4.22	3.62		22	19
4Al-4V	2G52235	4Al-4V	M1802D	.180	4.19	3.75		19	16
5Al-2½Sn	D1-220530	5Al-2½Sn	unknown	.237	4.78		2.23	14	10
6Al-4V	M2443	Ti-75A	M270	.227	3.15	2.14		22	18
4Al-4V	2G52235	Ti-75A	M270	.222	2.31	2.09		29	23
5Al-2½Sn	D1-220530	Ti-75A	M270	.286	3.01		1.43	9	7

[4] FAULKNER, G. E., "The Effects of Alloying Elements on Welds in Titanium, Part II," The Welding Journal, vol. 34(6), p. 295-s (June 1955).

[5] DALEY, D. M. and HARTBOWER, C. E., "The Notch Toughness of Weld Deposits in Commercial Titanium Alloys," WAL Report 401/221, The Welding Journal, vol. 35(9), p. 447-s (September 1956).
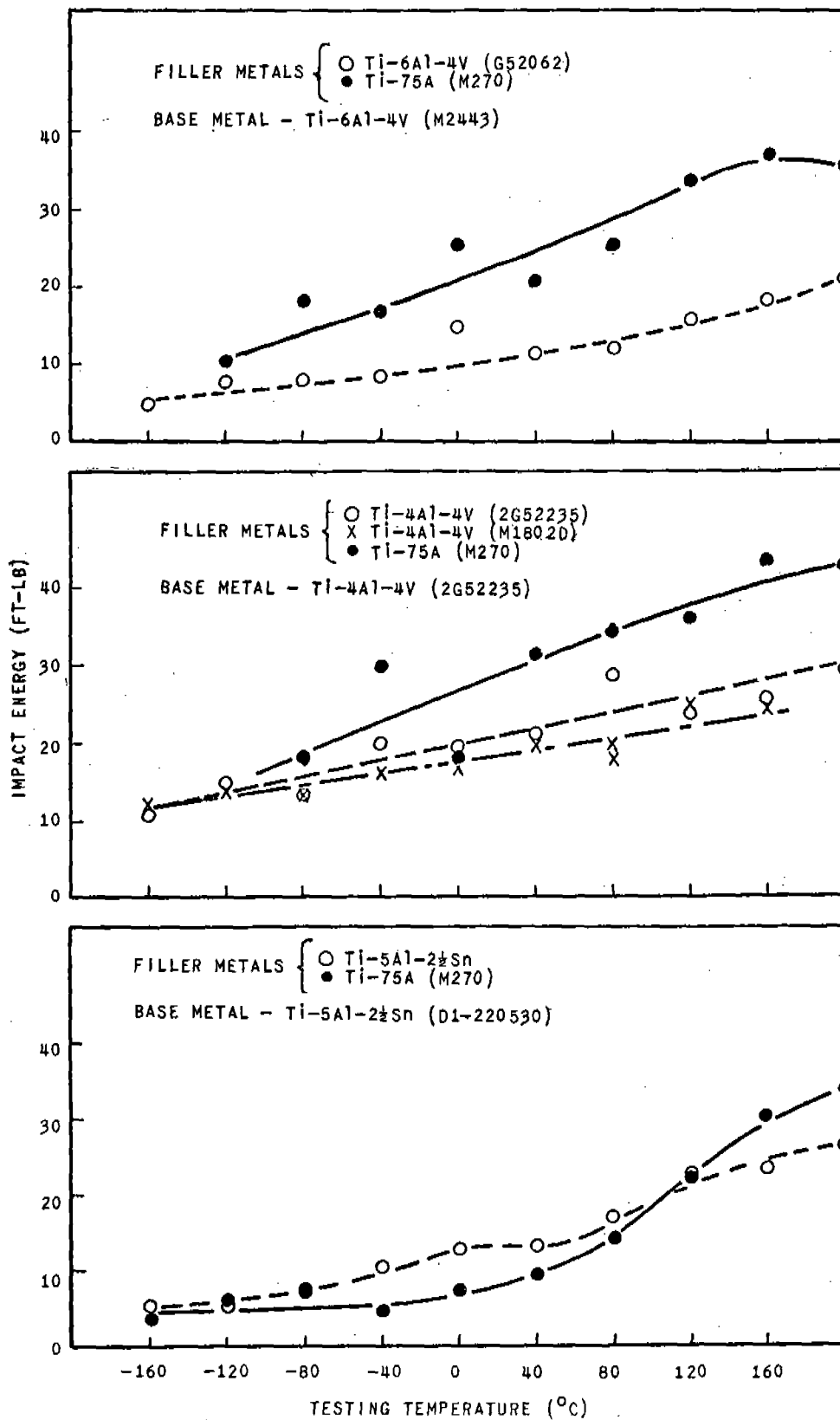
FIGURE 7: NOTCH TOUGHNESS OF WELD DEPOSITS prepared in titanium
alloys using either matching or unalloyed titanium filler material.

Hardness Tests

Vickers hardness surveys were run on each weldment. Impressions were placed at 0.02-inch intervals, starting in the base metal and traversing the heat-affected zone and deposited weld metal. The hardness data are plotted in Figure 8. Note that the hardness of the low-alloy weld deposits prepared by depositing unalloyed titanium in Ti-6Al-4V and Ti-5Al-2½Sn was considerably less than the weld deposits made using matching filler and base metal. No explanation is offered for the anomalously high hardness in the case of Ti-4Al-4V welded with unalloyed titanium filler. It is interesting to note in this connection that the yield strengths for the Ti-4Al-4V welded with matching and unalloyed filler wire were for all practical purposes the same; whereas, in the case of the Ti-6Al-4V and Ti-5Al-2½Sn higher yield strengths (and hardness) were realized with matching filler than with unalloyed filler.

Microstructure

Figure 9 illustrates typical microstructures of the Ti-6Al-4V base plate and welds made with matching filler and unalloyed filler. The base metal consisted of a fine deformed aggregate of alpha-beta phase. There is evidence of rolling direction in the base metal which in turn promotes directional properties as noted in the greater notch toughness in the transverse direction (see Figure 6). The microstructure of the outer HAZ (designated as A) indicates that recrystallization had occurred. The structure of the inner HAZ (B) adjacent to the weld deposit shows the presence of transformed beta in the
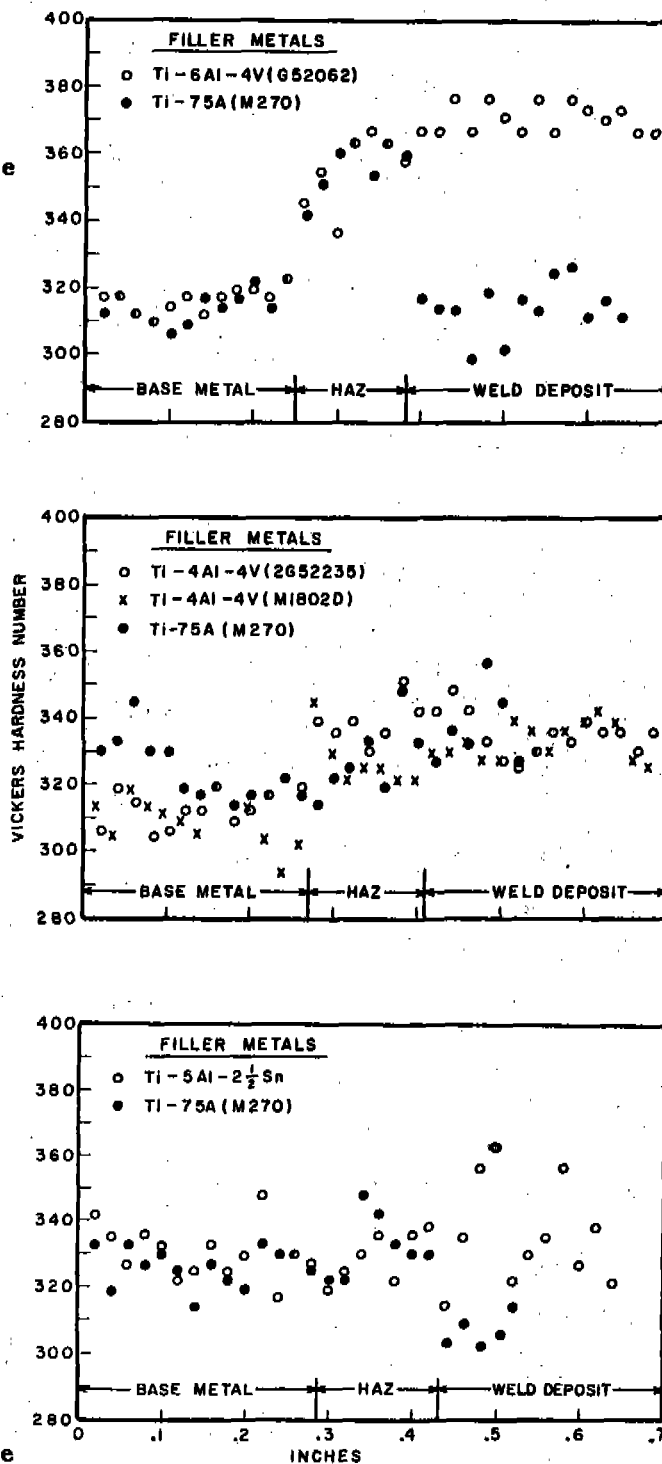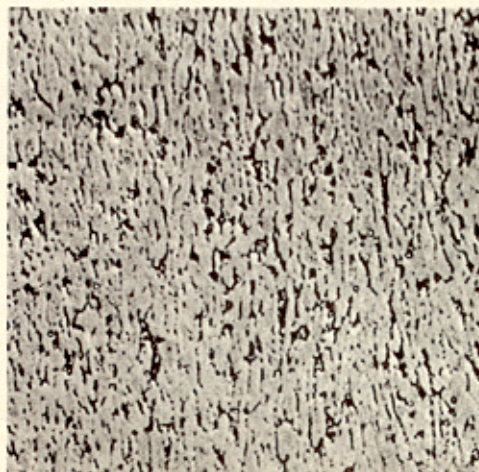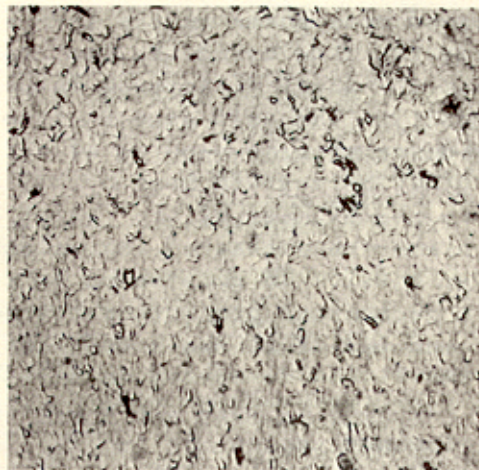

FIGURE 8: WELD JOINT HARDNESS SURVEY FOR ALLOYED TITANIUM WELDMENTS
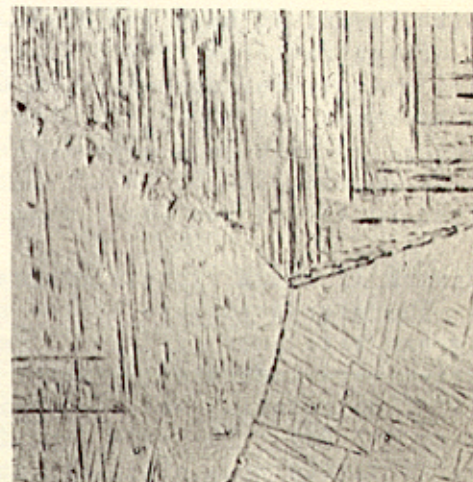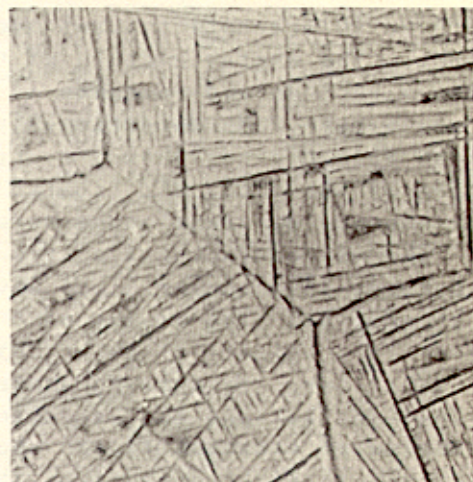
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Ti-6Al-4V WELDMENTS

HAZ (B)

HAZ (A)

BASE METAL

WELD DEPOSIT
Ti75A
FILLER METAL

WELD DEPOSIT
Ti-6Al-4V
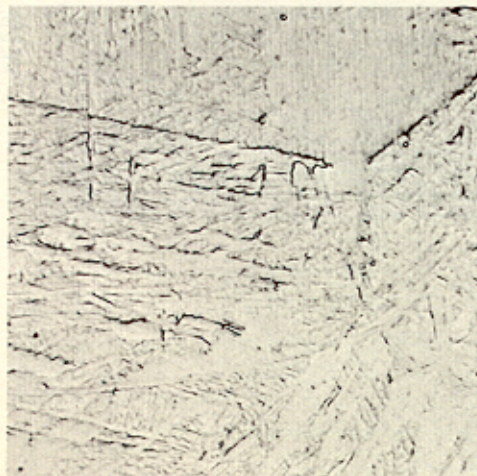FILLER METAL

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FIGURE 9: TYPICAL MICROSTRUCTURES (X500) FOR Ti-6Al-4V WELDMENTS prepared with the inert-gas-shielded consumable-electrode process.

form of medium fine acicular alpha. The weld deposit shows boundaries of the original beta grains with long fine acicular alpha phase present. This type of structure is correlated with the relatively high hardness (see Figure 8) and low notch impact value (see Figure 7) found in the weld metal. The microstructure of the weld deposit formed using unalloyed titanium filler metal consisted of more acicular alpha phase than the weld deposit made with the matching filler. This may account for the decrease in hardness (see Figure 8) and increase in notch toughness (see Figure 7) found in the weld made with unalloyed titanium filler.
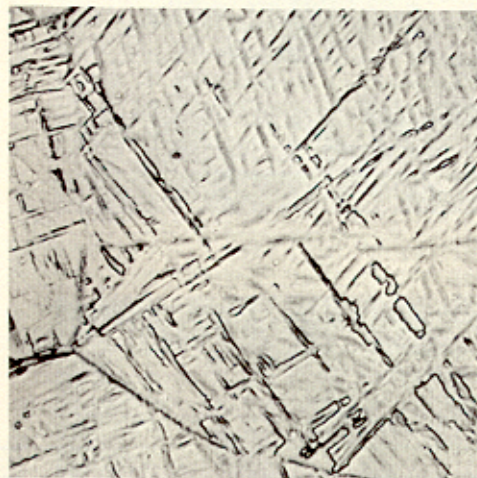
Figure 10 presents typical microstructures observed in the Ti-4Al-4V weldments. The microstructure of the base metal consisted of a coarse acicular structure and remnants of coarse basket weave associated with large grain size. No directionality is evident in this structure (notch toughness also did not show directionality, see Figure 6). The micro-structure of the outer HAZ labeled *(A)* and the inner HAZ *(B)* consisted of various amounts of transformed beta in the form of long needles of acicular alpha. The microstructures of the weld deposits formed with matching filler metal consist of acicular alpha with evidence of remnants of large beta grain boundaries. The amount of transformed beta phase in the form of acicular alpha appears to be approximately the same using the two heats of Ti-4Al-4V filler. This is consistent with the small difference in mechanical properties between the two alloy deposits. The weld deposit formed using *unalloyed titanium filler* shows evidence of fine needles of acicular alpha structure with remnants of the original beta grain boundaries. The notch impact value of this weld deposit is the highest of the series of weldments examined, and the hardness is higher than that of the weldment made with Ti-6Al-4V base and Ti-75A filler metal. In an attempt to correlate microstructures with difference in mechanical properties between the unalloyed filler deposited in 6Al-4V and 4Al-4V it was noted that the higher hardness and higher toughness in the Ti-75A deposited in 4Al-4V was associated with less acicularity and evidence of more alpha precipitation. It should also be noted that the aluminum content of the Ti-75A deposited in 4Al-4V was lower than in 6Al-4V (see Table VIII).

Figure 11 shows typical microstructures found in the Ti-5Al-2½Sn weldments. The microstructure of the base metal consisted of a small equiaxed alpha grain with some evidence of cold rolling, although no directional properties were indicated by notch toughness (see Figure 6). Increasing amounts of acicularity were found in traversing from the outer HAZ *(A)* to the inner HAZ *(B)*. The weld deposit consisted of coarse acicular alpha made up of fairly wide platelets and associated large grain size. This type of structure is usually associated with fairly low notch ductility (see Figure 7). The microstructure of the weld deposit produced with unalloyed filler is similar to that of the Ti-5Al-2½Sn base welded with matching filler metal. The only difference between the microstructures of the matching and unalloyed fillers is evidence of more precipitation in the case of Ti-75A deposited in 5Al-2½Sn. The coarse acicular structure consisting of wide platelets is usually related to the low notch ductility. It is possible that the relatively high interstitial content (COHN) in this weld deposit may also have contributed to its low notch ductility.
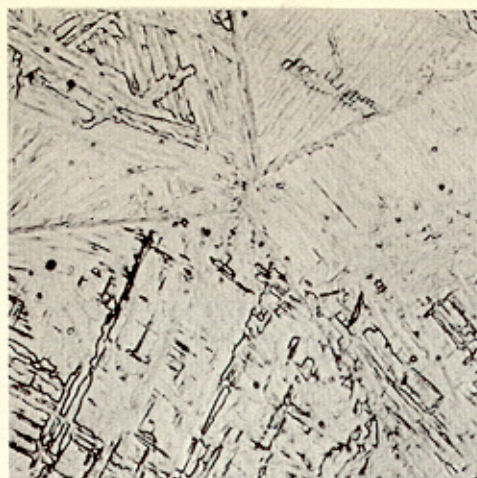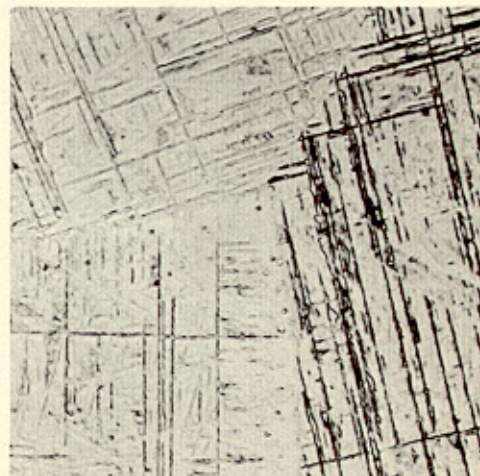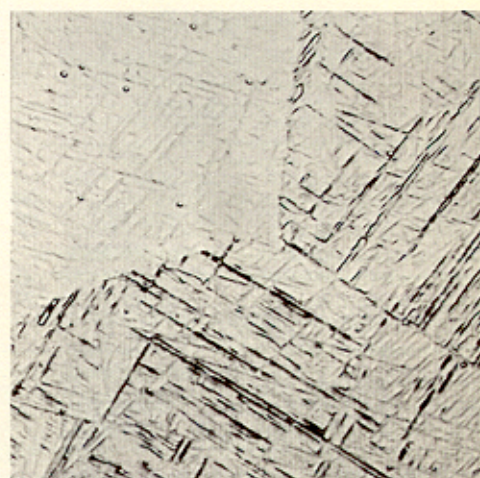
Ti-4Al-4V WELDMENTS

HAZ (B)

WELD DEPOSIT
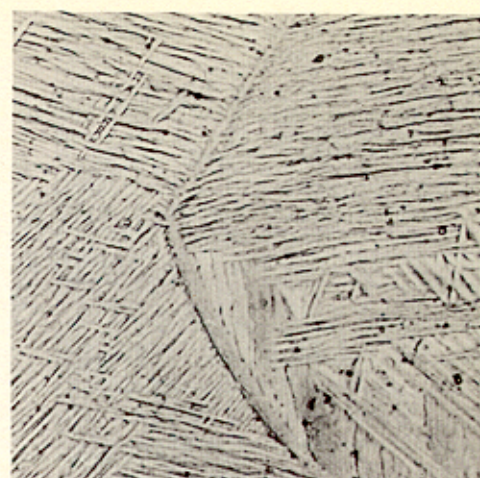Ti75A
FILLER METAL

HAZ (A)

WELD DEPOSIT
Ti-4Al-4V
FILLER METAL (2)

BASE METAL
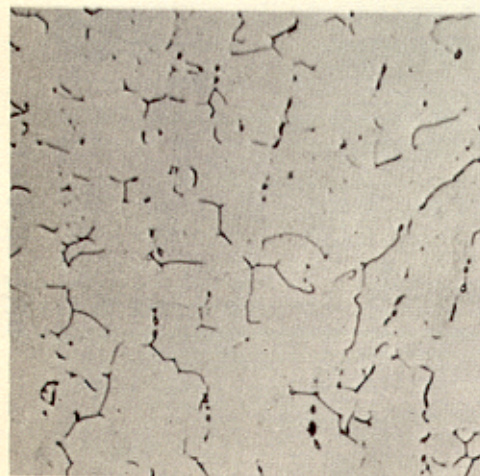
WELD DEPOSIT
Ti-4Al-4V
FILLER METAL (1)

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FIGURE 10: TYPICAL MICROSTRUCTURES (X500) FOR Ti-4Al-4V WELDMENTS prepared with the inert-gas-shielded consumable-electrode process.

Ti-5Al-2½Sn WELDMENTS

HAZ (B)

HAZ (A)

BASE METAL

WELD DEPOSIT
Ti75A
FILLER METAL
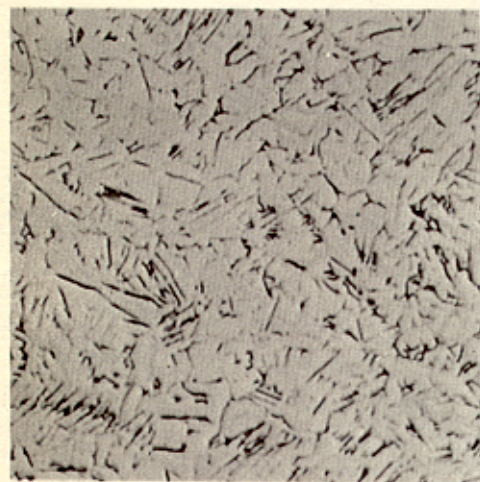
WELD DEPOSIT
Ti-5Al-2½Sn
FILLER METAL

Wtn. 639-15,951

FIGURE II: TYPICAL MICROSTRUCTURES (X500) FOR Ti-5Al-2½Sn WELDMENTS prepared with the
inert-gas-shielded consumable-electrode process.

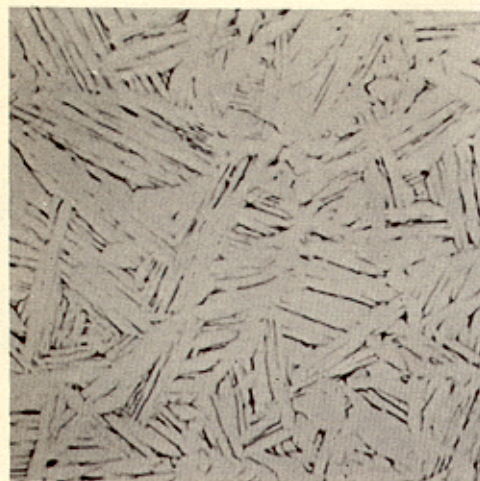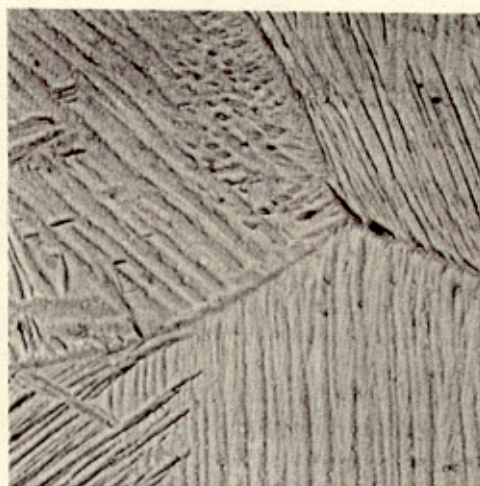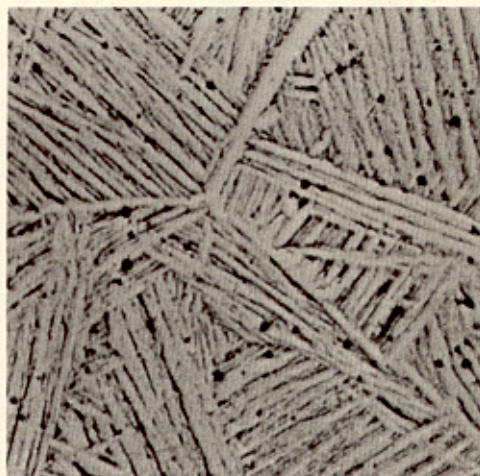## SUMMARY AND CONCLUSIONS

Remarkably similar test results were revealed (considering that different heats and different welding processes were under investigation) when comparison was made between the tensile and impact data obtained in this investigation using a consumable-electrode single-pass weld and that of an earlier study using a two-pass tungsten arc weld (Table IX).

TABLE IX

| Material | | | | Tensile | | | Impact |
Alloy	Heat	Test	Welding Process	Yield 0.2% (KIPS)	Ulti-mate (KIPS)	R.A. (%)	-40°C (ft-lb)
6Al-4V	M1801D	Base Metal	--	134	149	44	22
		Transv. Weld	2-pass W-arc*	132	152	32	--
		All Weld Metal	2-pass W-arc*	130	148	32	9
6Al-4V	M2443	Base Metal	--	135	148	42	18
		Transv. Weld	1-pass Consum.**	138	152	44	--
		All Weld Metal	1-pass Consum.**	134	154	14	9
5Al-2½Sn	D30540B	Base Metal	--	122	136	41	13
		Transv. Weld	2-pass W-arc*	118	130	25	--
		All Weld Metal	2-pass W-arc*	121	133	25	10
5Al-2½Sn	D1-220530	Base Metal	--	133	138	43	11
		Transv. Weld	1-pass Consum.**	132	142	38	--
		All Weld Metal	1-pass Consum.**	135	144	28	10

*Double-V butt tungsten-arc weld (matching filler) - see Reference 1.
**Single-V butt consumable-electrode weld (matching filler).

Using matching filler and base metal, the weldments developed 100% joint efficiency. There was, however, some loss of ductility which was generally most evident in the all-weld-metal (longitudinal tensile) specimens. In the case of the Ti-5Al-2½Sn and the Ti-4Al-4V welded with matching filler the toughness of the weld deposits was approximately the same as the unwelded plate. The Ti-6Al-4V, however, consistently showed a loss of toughness as the result of welding. Of the three composition types investigated Ti-4Al-4V had the best toughness.

Using unalloyed filler material there was a loss of joint efficiency. However, a decided improvement in notch toughness was realized in the case of the two alloys containing vanadium; whereas, the all-alpha Ti-5Al-2½Sn suffered a loss of toughness as the result of welding with an unalloyed filler.

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ACKNOWLEDGMENT

The authors are particularly grateful to Dr. Everett L. Reed, Research Adviser in the Materials Engineering Laboratory, for preparation and analysis of the metallographic specimens (see pages 14 - 18 inclusive).

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